Simple Comb Generator Design for SWaP-Constrained Applications

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***Abstract*— Many wireless devices have requirements that emphasize low size, weight and power for increased functionality and extended lifetimes. The additional complexity of these devices mandates the need to dynamically verify that all sub-system functions are fully operational. These tests can only be performed internal to the unit, and a circuit that could be utilized to meet this demand should be constructed to be as simple as possible. The design of a compact comb generator circuit using a step recovery diode is analyzed and the prototype results presented in this paper. This simple circuit requires no bias voltage, and effectively produces harmonics up to 2 GHz with a 2 MHz input signal, which is sufficient for adding built-in test capability to most wireless devices.**

***Index Terms*— Comb generator, pulse generator, step recovery diode, SRD.**

I. Introduction

Comb generator circuits are used to intentionally create multiple harmonics of an input signal and have been around since the 1960s. While they can be found in a variety of applications, one of their most common functions is for test equipment calibration, which includes the error correction of vector network analyzers, spectrum analyzers and sampling oscilloscopes. In addition to these calibration tasks, comb generators are used in frequency multipliers, fast frequency hopping synthesizers, anechoic chamber verification and electromagnetic compliance testing [1], [2].

Many wireless devices that are typically focused on reduced size, weight and power (SWaP) can also benefit from the inclusion of a comb generator circuit to provide built-in test (BIT) capability. The ability to verify that critical parts of a complex system are properly functioning is becoming more useful as the cost of consumer electronics is increasing. For example, a smartphone that could diagnose itself and report that a certain integrated circuit has failed could not only significantly reduce repair time, but also ultimately result in fewer disposed devices. In order to make the inclusion of a comb generator for BIT capability feasible in more devices, however, the circuit itself has to be physically compact and draw minimal power.

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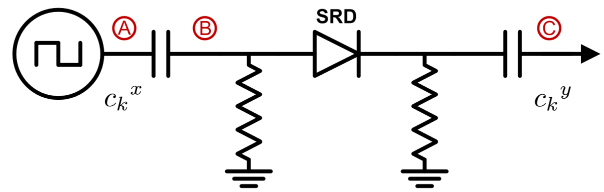

Fig. 1. Comb generator circuit diagram, including a step recovery diode (SRD), with stage and equation labels.

Presented in this paper is a simple discrete-component comb generator circuit that was designed around a step recovery diode (SRD), requires no supply voltage and maintains a small footprint on a printed circuit board (PCB). This circuit can easily be incorporated into systems that require BIT capability, including receiver and ADC verification.

The circuit design will be discussed in Section II, while the measured results will be presented in Section III. Conclusions will be derived in Section IV.

II. Comb Generator Design

All comb generator circuits require an input signal, which is utilized to drive the output. This input signal is typically a single frequency, and establishes the harmonically-related tone spacing in the frequency domain of the comb output. For example, if the input has a frequency of 1 MHz, then the output of the comb generator will have tones spaced at 1 MHz.

The circuit described in this paper will be demonstrated with a fixed crystal oscillator, but this input could be substituted for another signal, such as an external input or a preexisting system clock. The block diagram of the circuit discussed here is shown in Fig. 1. The oscillator used in this design provides a square-wave output, but other input signal types would also work. If tighter frequency stability is a requirement, a temperature-controlled crystal or another higher performance oscillator could be used. An oscillator with a square-wave output is described by the Fourier series coefficients

$$c_k{}^x = -j\frac{A_{in}}{\pi k}[1-(-1)^k], \tag{1}$$

where A_{in} is the maximum output voltage and k is the frequency number. Since the function exhibits even

symmetry in the time domain, all the even harmonics are zero.

Following the oscillator is a series capacitor and shunt resistor that together form a passive differentiator. This simple first-order high-pass filter extracts the edges of the square wave to yield positive and negative impulses. This filter's ideal frequency response is represented by

$$H(j2\pi k) = \frac{1}{1 + \frac{1}{j2\pi kRC}}, \tag{2}$$

where R and C are the resistor and capacitor values, respectively. In addition to being part of the differentiator, this shunt resistor provides a passive- or self-biasing capability when combined with the shunt resistor after the diode. These two resistors together allow the circuit to operate without an external supply voltage.

The main component of this comb generator circuit is a step recovery diode (SRD), which is a specially-doped PIN junction diode that can be used as a charge-controlled switch. When forward-biased, the diode exhibits a low impedance and stores charge in the intrinsic region. When an SRD is suddenly reverse-biased, it will continue to appear as a low impedance until all of the stored charge is removed, at which time it will abruptly change to a high-impedance state [3]. The result of this diode operation is that the positive impulses of the differentiator are sharpened, while the negative ones are nearly eliminated. This effectively breaks the even symmetry of the input signal, and generates both odd and even harmonics at the SRD output.

Assuming a square-wave input and considering the SRD's response described above, the comb generator's output can be approximated as a series of exponentially-decaying sawtooths, given by

$$y(t) = \sum_{n=-\infty}^{\infty} A_{out} e^{-\alpha(t-nT_0)} u(t - nT_0), \tag{3}$$

where A_{out} is a scaled version of the input voltage A_{in}, α is the decay rate that controls the pulse width, T_0 is the pulse repetition period and $u(t)$ is the unit step function. The decay rate must be a positive number to ensure that the function properly decreases. Since this function is periodic, it can be represented by the Fourier series coefficients

$$c_k{}^y = \frac{A_{out}}{\alpha T_0 + j2\pi k}, \tag{4}$$

which shows that both even and odd harmonics are created at the comb generator's output as desired. A non-linear transmission line (NLTL) [4], bipolar junction transistor (BJT) [5], or another non-linear element could have been used instead of the SRD and could possibly have overcome some of the SRD's disadvantages, particularly higher phase noise, but such devices are typically more complex and require more physical area to implement.

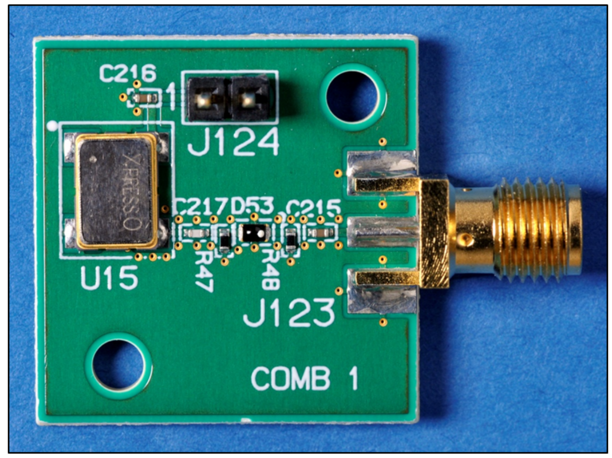

Fig. 2. Comb generator prototype board measuring 2.3 x 2.3 cm.

It was already mentioned that the shunt resistor at the output of the SRD provides self-biasing for the diode, but it was also used to match the diode's output to a broadband 50 Ohm impedance, which is in contrast to using inductors or other narrowband elements. Finally, the output capacitor was included to block the DC bias current from the output connector.

III. Results

For the prototype measurements discussed in this section, the abovementioned circuit was implemented with the following components. The square-wave oscillator was from the FXO-HC73 series of crystal oscillators by Fox Electronics and was housed in a small surface mount package. This part provided an amplitude, A_{in}, of 1.0 V, with an output frequency of 2 MHz. This frequency was chosen to verify the circuit concept, but different input frequencies could be used instead by scaling the other circuit parameters. The differentiator was comprised of an 82 pF capacitor and 100 Ohm resistor, while the SRD chosen was a surface mount diode from the MSD700 series by Aeroflex, which had a minority carrier lifetime of 21 ns and a transition time of 150 ps. Finally, the output resistor was set to 50 Ohms and the output capacitor was a broadband 100 nF. A photo of this prototype circuit board is shown in Fig. 2, and measures 2.3 x 2.3 cm.

In order to gain insight into the circuit's operation, measurements were taken at several different stages, as indicated by the letters (A, B, C) in the block diagram of Fig. 1. The time-domain output of the square-wave oscillator is shown in the top plot of Fig. 3; this is the comb generator circuit's input signal. The middle plot of Fig. 3 indicates the time-domain signal obtained after the differentiator, and clearly shows the edges of the square wave being extracted from the input signal. Finally, the bottom plot of Fig. 3 displays the comb generator output in the time domain, and contains the positive impulses

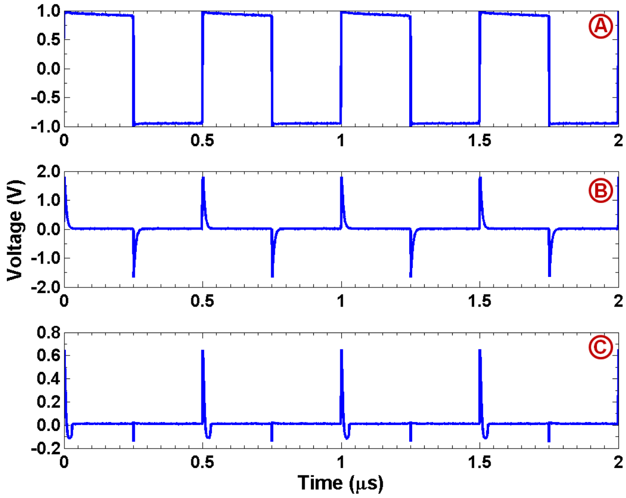

Fig. 3. Time-domain plots showing the signal at different stages of the circuit, as referenced in Fig. 1.

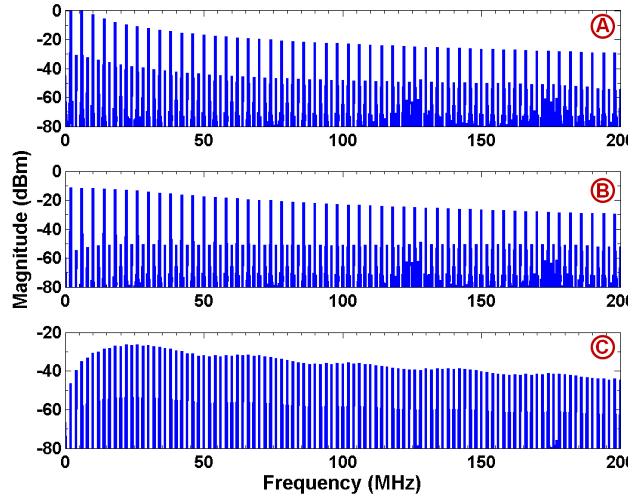

Fig. 4. Frequency-domain plots showing the signal at different stages of the circuit, as referenced in Fig. 1.

that were modeled as exponentially-decaying sawtooths in Section II. These pulses have a full width at half maximum (FWHM) of 4.1 ns and an amplitude of 0.65 V. Due to the fact that the SRD conducts for a short time when reverse-biased, a suppressed version of the negative impulses also appear, but do not degrade the comb's combined output.

The frequency-domain plots corresponding to the same points in the circuit are shown in Fig. 4. By comparing these images with their time-domain representations in Fig. 3, the contributions of each stage can be appreciated. The upper display of Fig. 4 shows the oscillator harmonics spaced at 4 MHz, which is twice the crystal frequency. The output of the differentiation stage is plotted in the middle of Fig. 4, and illustrates the high-pass filtering function that attenuates the lower frequency signals. The even symmetry of both the oscillator and differentiated signals is seen to suppress the even harmonics by more than 20 dB, as expected. Lastly, the frequency-domain plot of the complete comb generator is depicted at the bottom of Fig. 4. The output harmonic tones are evenly spaced at multiples of the 2 MHz input frequency. Over the 100 harmonics represented in this plot, the tone amplitudes are found to vary by a maximum of 18 dB and have at least 40 dB signal-to-noise ratio, which is sufficient for most applications.

The wideband performance of this comb generator prototype was also evaluated and its frequency-domain output is expanded in Fig. 5. While this specific application focused on harmonics below 200 MHz, the overall magnitude response exhibits a less than 10 dB roll-off between 500 and 2000 MHz. This could be improved with additional high-pass filtering to better equalize performance over the band of interest.

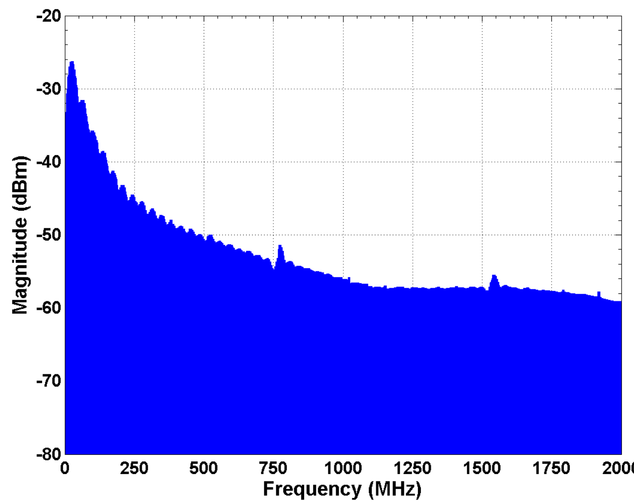

Fig. 5. Wideband frequency-domain output of the comb generator circuit.

IV. Conclusion

The dynamic verification of most low-SWaP wireless devices can be augmented with a compact comb generator. This paper described and analyzed the individual stages of such a circuit using a self-biased step recovery diode for the generation of wideband output harmonics. The design produced time-domain impulses with FWHM pulse widths of 4.1 ns, which extended the frequency-domain harmonics out to 2 GHz using an input signal of 2 MHz. The simplicity of this comb generator allows it to be incorporated into many devices to add or enhance their built-in test capability, which can verify both sub-system and complete-device functionality.

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